Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

VOLUME XXVII NUMBER 4

THE
JOURNAL OF GEOLOGY
MAY-JUNE 1919

THE BUILDING OF THE COLORADO ROCKIES

ROLLIN T. CHAMBERLIN
The University of Chicago

PART II

THE LYONS-GRAND RIVER SECTION

After a consideration of alternative locations for the contemplated study of the Colorado Rocky Mountain diastrophism, a section across the folded belt between the Great Plains north of Denver and the Uinta Basin west of Glenwood Springs was selected as offering the most promise. Among the advantages thus offered, it may be noted that this section would bring in the characteristic *en échelon* structure of the eastern foothills, here specially declared;[1] it would cross the Front Range where strongly developed; it would embrace the wide area of sedimentary rocks in Middle Park; it would traverse a typical section of the Park Range, and finally beyond this it would extend across the most representative strip of the slightly disturbed sedimentary belt to the Grand Hogback which terminates the Rocky Mountain folding on the west. Such a section, furthermore, would be across one of the wider portions of the Colorado Rockies. There was a further advantage growing out of the fact that the Colorado Rockies embrace extensive areas of pre-Cambrian granite and other crystalline rocks. Over such areas of old crystalline rocks it is difficult to reconstruct the folds, since these areas afford only the most meager information as to the nature of the post-Cretaceous folding and as a result are little better than blank pages in the later diastrophic story. It was therefore advisable to choose a section which, though it be typical of the mountain system as a whole, still crossed the granite belts where they are narrowest, and where the belts of folded sedimentary rocks are widest. This was accomplished in the section chosen.

---

[1] This has recently been described by Victor Ziegler, "Foothills Structure in Northern Colorado," *Jour. Geol.*, XXV (1917), 715-40.

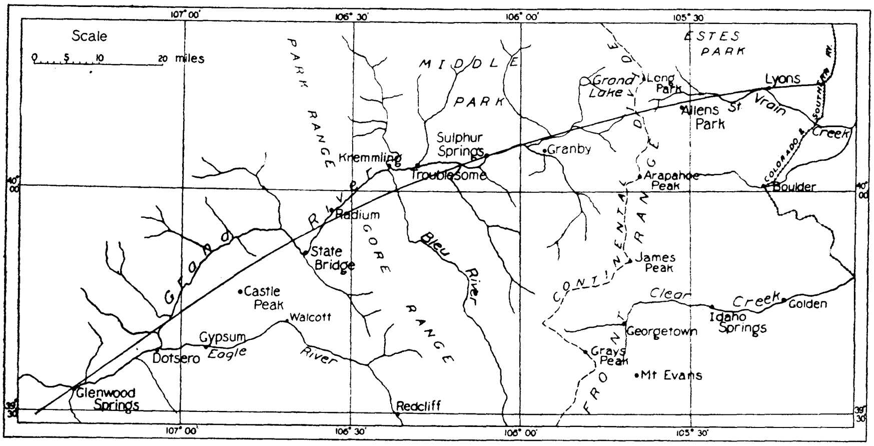

FIG. 4.—Map of the Lyons–Grand River section. The section extends along a curved line from the Colorado and Southern Railroad east of Lyons, to the western slope of the Grand Hogback southwest of Glenwood Springs, a total distance of 135 miles. Because of the adopted curvature the line of the section crosses the axial lines of the folds approximately at right angles.

The section finally selected for measurement has as its eastern terminus the bend of the Colorado and Southern Railroad tracks, 4½ miles north of the town of Longmont (Niwot sheet, T. 3 N., R. 69 W., Sec. 11, middle of S. line). From this point westward the line of section was drawn so as to strike the bench mark (5,375 feet) in the town of Lyons, to pass onward through Allen's Park, and across the continental divide one-fifth of a mile north of Oglala Peak (13,147 feet). On the Pacific slope it continues westward in the general vicinity of the Grand River, runs by the railroad station at Hot Sulphur Springs, passes 2⅓ miles north of State Bridge, and finally crosses the city of Glenwood Springs and the Grand Hogback to the flat-lying strata of the Uinta Basin, 6¼ miles southwest of Glenwood Springs (Fig. 4).

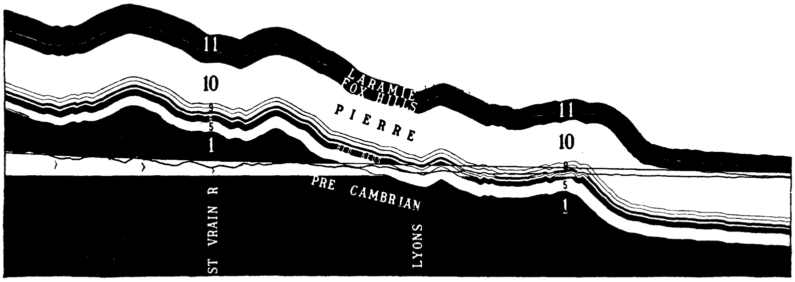

FIG. 5.—Lyons sheet (No. 1) on the east and St. Vrain sheet (No. 2) on the west. The restored folds include all beds to the top of the Laramie. The principal formations are: (1) pre-Cambrian granite; (5) Fountain and Lyons sandstones; (6) Lykens (red beds); (7) Morrison; (8) Dakota; (9) Benton and Niobrara; (10) Pierre; (11) Fox Hills and Laramie. The layers have been left unshaded throughout a horizontal strip whose base represents a level 5,000 feet above the sea, and whose top is the tilted peneplain surface. The profile of the present land surface is represented by a line which lies for the most part within this unshaded strip. Each sheet represents a horizontal distance of ten miles.

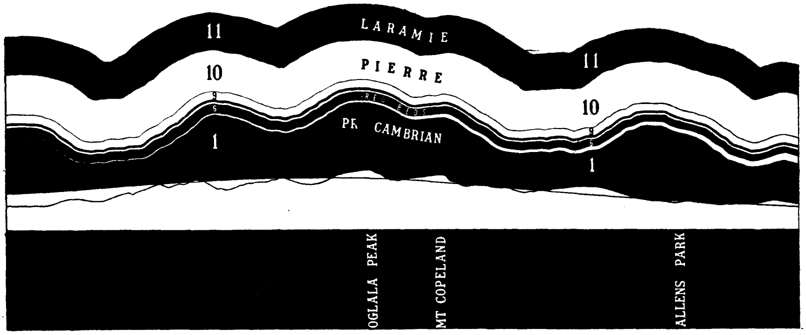

FIG. 6.—Allen's Park sheet (No. 3) on the east and Continental Divide sheet (No. 4) on the west. The peneplain here reaches its greatest elevation. A few monadnocks rise above the bowed peneplain and today constitute the high peaks of the Front Range. Fig. 6 represents a horizontal distance of twenty miles.

The trace of this section drawn on the map is not a straight line, for it was purposely given a slight curvature that it might cross the trends of the different folds as nearly at right angles as possible. This curvature was necessitated by the fact that the individual ranges are not parallel to one another, but converge toward the south. The curved section crossing these ranges at right angles, and hence also normal to the axial lines of the folds, has its convex side therefore facing northwest. The total length of the section measured on this slight curve is 135 miles.

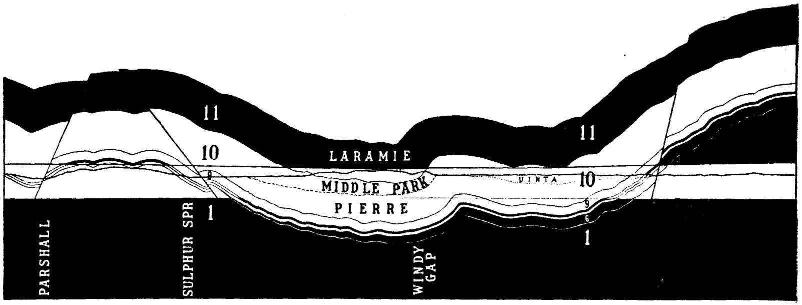

FIG. 7.—Granby sheet (No. 5) on the right and Sulphur Springs sheet (No. 6) on the left. The Middle Park (early Tertiary) beds occupy a part of the structural basin between Windy Gap and Sulphur Springs while the Uinta beds appear in the lesser basin in the middle of the Granby sheet.

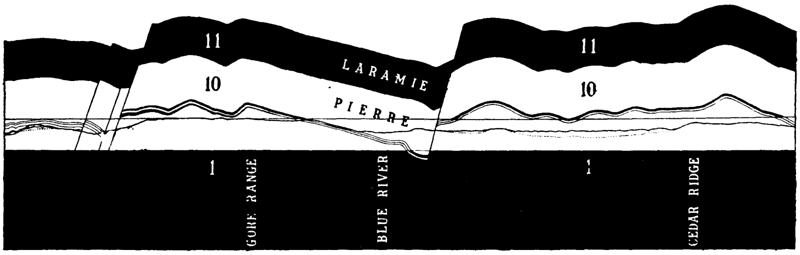

FIG. 8.—Troublesome sheet (No. 7) on the east and Gore Range sheet (No. 8) on the west. The formations are: (1) pre-Cambrian granite; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Colorado and Pierre; (11) Fox Hills and Laramie. Basin of Uinta beds in the middle of the Troublesome sheet. The peneplain rests upon the broad crest of the Gore Range.

The topographic sheets of the United States Geological Survey as yet cover only the eastern portion of this selected section. Here the Niwot, Boulder, and Long's Peak sheets were a great help in locating the field observations and in plotting the cross-section. West of the Long's Peak quadrangle, one had to be satisfied with the land surveyor's map of Grand County and the Department of Agriculture's Forest Service map of the Holy Cross National Forest, which together cover the remainder of the section.

Throughout this section of 135 miles, the dips of the strata were read wherever obtainable, and were plotted to scale as the basis for the reconstruction of the original folded structure. Compared with the Pennsylvania Appalachians, the Colorado Rockies present greater obstacles to an investigation of this sort, because it is impossible to obtain equally complete data. In the Appalachians of Pennsylvania the sedimentary beds still persist throughout the mountainous region to such an extent that from the remnants the original outlines of the folds may be reconstructed with the assurance of reasonable accuracy. But among the Colorado

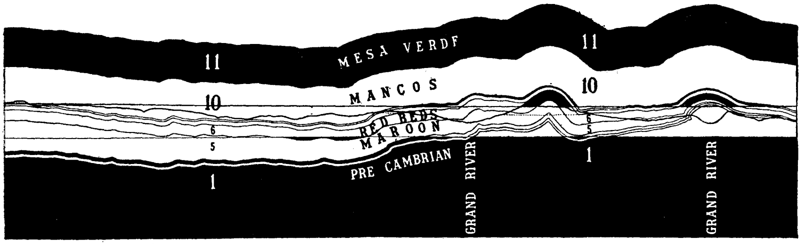

FIG. 9.—State Bridge sheet (No. 9) on right and Castle Peak sheet (No. 10) on left. Formations: (1) pre-Cambrian; (2) Sawatch; (4) Blue limestone; (5) Weber and Maroon formations; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Mancos; (11) Mesa Verde.

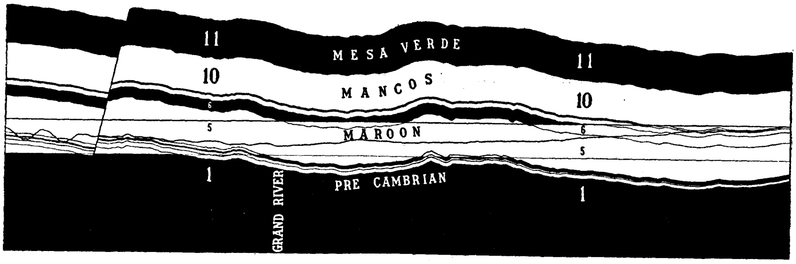

FIG. 10.—Gypsum sheet (No. 11) on the right and Dotsero sheet (No. 12) on the left. The peneplain level appears high above the present surface because this section is within the Grand River Valley. Conventions as before.

Rockies the deformed sedimentary strata, to which one must look for the record of the folding, have been completely removed from large areas by the great denudation which the region has suffered. In those areas the pre-Cambrian granites and gneisses now constitute the surface formation. Over such crystalline areas folds can be projected only diagrammatically and a large element of error, or at least of uncertainty, is necessarily involved. In Middle Park, sediments of Uinta age, deposited after the folded ranges had been greatly eroded, now hide from view several miles of the deformed terranes. Tertiary basaltic lava flows also effectively conceal the folded structures at a number of places in the section. Of these difficulties the basaltic lava covers are the least formidable, owing to their lesser area and more patchy pattern, which makes it possible in many places to infer the concealed structure from nearby outcrops of the folded beds. But the combination of these adverse conditions makes the Colorado Rocky Mountain section far less satisfactory than that of the Appalachians.

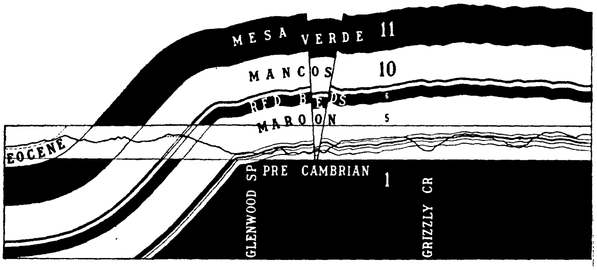

FIG. 11.—Glenwood Springs sheet (No. 13) and Grand Hogback sheet (No. 14), which covers the westernmost five miles of the section. Formations: (1) pre-Cambrian granite; (2) Sawatch; (3) Yule limestone and Parting quartzite; (4) Leadville limestone; (5) Weber and Maroon; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Mancos; (11) Mesa Verde. Upturned Eocene beds (mostly Wasatch) on west margin of Grand Hogback sheet.

The entire cross-section of 135 miles was plotted on a scale of $\frac{1}{31680}$ on sheets of co-ordinate paper 20 inches in length, thus making each sheet cover 10 miles of section. Thirteen and a half sheets thus compose the plotted section. But in computing the amount of crustal shortening and the thickness of deformed shell, the most easterly 3 miles of the section were excluded from consideration because they are truly a part of the plains and do not properly belong to the folded belt. The truly folded section is thus reduced to 132 miles in length (Figs. 5–11).

THE SHORTENING OF THE CRUST

Folding of strata under horizontal compressive stress is necessarily accompanied by a horizontal shortening of the deformed portion of the earth shell. The compressed mass is shortened in at least one of its horizontal dimensions, while it relieves itself by bulging upward in the direction of least resistance. The first objective in our problem is to determine the amount of horizontal crustal shortening which the Rocky Mountain region underwent while writhing in the throes of diastrophic revolution. The original length of the Lyons–Grand River section before folding may be determined with some approximation by measuring the total length of a selected layer through all the sinuous bends and wrinkles which are recorded on the plotted cross-section. A small corrective factor for the compacting of materials under the compression is to be introduced. The present horizontal length to which the section has been compressed is simply the map distance between the two ends of the section measured along the slight curve which was chosen so that the section shall cross the folds at right angles as explained on page 227. The difference between the length of the strata followed through all the folds and faults as reconstructed and the present map distance of the same section is the approximate shortening which the earth shell has suffered in being crumpled into mountains.

For measuring the length of the wrinkled strata all members of a thick series of sediments are not likely to be of equal value. In folds of the type technically known as similar, the individual beds have all been folded with the same curvature.[1] But in parallel folds, where the bedding surfaces are mutually parallel, the curvature of no two beds is exactly the same, and this difference in curvature implies the dying out of the folds in one direction or the other from a given bed. Hence an element of error is likely to be introduced in the hypothetical projection of younger beds over eroded anticlines, or of older beds in the troughs of deep synclines. This error increases with the vertical distance from the observed stratum. It is clear therefore that cross-section measurements designed to give the crustal shortening should be made on stratigraphic horizons as near as practicable to those on which the field observations were actually made. The error of mechanical projection is then less serious.

---

[1] C. K. Leith, *Structural Geology* (1913), pp. 106–7.

Competent and incompetent beds also behave differently in folding. Various secondary adjustments between the different beds are, in many cases, accomplished by minor contortions and subordinate movements within the readily yielding incompetent layers, which, by accommodating themselves in buffer-like fashion to the major movements, facilitate the folding. The strong, competent layers, less subject to local irregularities, are likely to reveal truer estimates of the shortening of a region as a whole.

The ideal horizon for measurement should therefore have the following qualities: It should be stratigraphically near the beds on which the observations were actually made; it should be the top or bottom of a rather thin formation so as to limit variability; the formation should be resistant and hence predisposed to outcrop sharply in the field; it should be readily distinguished from other formations; and it should be so located in the column as to come to the surface at many places in the section. Such a formation in the Colorado Rockies is the Dakota sandstone. It is one of the most persistent and conspicuous of the formations, and it occupies the desired mean position in the stratigraphic column. The base of the Dakota sandstone was therefore adopted as the line to be measured in these studies.

On the cross-section sheets the base of the Dakota was followed through all the recorded folds and crenulations with a thin, flexible copper wire, which was bent so as to conform to every change of curvature. The wire was then straightened and compared with the scale for measurement. The difference between the length of the base of the Dakota, as thus measured along all the sinuosities of the section, and the present horizontal length of the section gives the amount of crustal shortening. Measuring each of the fourteen sheets separately gave the following results:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	
Length following base of Dakota sandstone	7.80
Present horizontal length	7.00
Shortening	.80
No. 2. St. Vrain sheet	
Length following base of Dakota sandstone	10.91
Present horizontal length	10.00
Shortening	.91
No. 3. Allen's Park sheet	
Length following base of Dakota sandstone	10.805
Present horizontal length	10.00
Shortening	.805
No. 4. Continental Divide sheet	
Length following base of Dakota sandstone	10.89
Present horizontal length	10.00
Shortening	.89
No. 5. Granby sheet	
Length following base of Dakota sandstone	11.085
Present horizontal length	10.00
Shortening	1.085
No. 6. Sulphur Springs sheet	
Length following base of Dakota sandstone	10.65
Present horizontal length	10.00
Shortening	.65
No. 7. Troublesome sheet	
Length following base of Dakota sandstone	10.45
Present horizontal length	10.00
Shortening	.45
No. 8. Gore Range sheet	
Length following base of Dakota sandstone	10.275
Present horizontal length	10.00
Shortening	.275
No. 9. State Bridge sheet	
Length following base of Dakota sandstone	10.635
Present horizontal length	10.00
Shortening	.635

	Miles
No. 10. Castle Peak sheet	
Length following base of Dakota sandstone	10.20
Present horizontal length	10.00
Shortening	.20
No. 11. Gypsum sheet	
Length following base of Dakota sandstone	10.235
Present horizontal length	10.00
Shortening	.235
No. 12. Dotsero sheet	
Length following base of Dakota sandstone	10.29
Present horizontal length	10.00
Shortening	.29
No. 13. Glenwood Springs sheet	
Length following base of Dakota sandstone	10.265
Present horizontal length	10.00
Shortening	.256
No. 14. Grand Hogback sheet	
Length following base of Dakota sandstone	6.20
Present horizontal length	5.00
Shortening	1.20
Summation: Entire Lyons–Glenwood Springs section	
Total original length (base of Dakota sandstone)	140.69
Present horizontal length	132.00
Total shortening	8.69

According to these measurements, the lateral thrusting which produced the Colorado Rockies compressed 140.69 miles of country into 132 miles, thus bringing two points on opposite sides of the folded belt 8 miles closer together than they were before the folding commenced. A crustal shortening of 8 miles distributed throughout a belt of originally 140 miles in breadth does not indicate very intense horizontal thrusting. The horizontal compression was much less than in the Pennsylvania Appalachians west of Harrisburg, where 81 miles were compressed into 66 miles, thus involving a shortening of 15 miles in this much narrower belt.[1] The

---

[1] *Jour. Geol.*, XVIII (1910), 235.

Colorado Rockies are therefore mountains in which the horizontally operating forces have achieved only moderate results. Farther north in Montana and Alberta, however, the great overthrust faults on the Rocky Mountain front imply that the horizontal thrusting has there been much greater.

THE ELEVATION OF THE FOLDED TRACT

When a region is folded by compressive stress, the horizontal shortening is compensated by vertical bulging, except in so far as there be an actual reduction in the volume of the material deformed. According to our fundamental postulate, if the amount of crustal shortening and the amount of the resulting vertical bulge be known, the thickness of the folded shell may be calculated. It is next in order to determine, if possible, the amount of vertical uplift which has resulted from the folding.

The first requisite for the determination of the amount of upswelling is a datum-plane above which the heights of the folds are to be measured. This datum-plane should coincide in position with the original surface of the region just before the folding commenced. The chief difficulty is to locate a datum-plane available today which will correspond in position to the original surface before folding. Mountains ideally built for such a study should be folded from a plain which was just at sea-level. A minimum of epeirogenic movement should accompany the orogenic disturbance. Then without the entrance of any other diastrophic changes to add complications, erosion should again reduce the folded tract completely to base level. This base level should correspond as closely as possible to the sea-level from which the mountains originally rose. This base level would then constitute the proper datum-plane above which to measure the heights of the folds.

The history of the Colorado region has been such as to render it rather well suited to a treatment of this sort. The closing stages of the Cretaceous period in Colorado witnessed a transition from the conditions of marine sedimentation to those of terrestrial deposition. Among the last beds laid down before the inauguration of the Laramide folding were vegetable accumulations which have since become coal. They were presumably formed in marshes which were very close to sea-level. The Colorado sea-level at the close of the Cretaceous thus becomes the critical level. It was a plain approximately at sea-level which was arched and wrinkled into the Rocky Mountains by the diastrophic throes of the dying Mesozoic. Erosion by the rapid streams which sprang into being assailed the uplifted ranges and in time reduced them to the condition of a peneplain. But was, or was not, the level of this peneplain approximately the same as the level of the plain which earlier was folded into the mountains, and whose position today is such an important factor in our problem?

If it were known that the peneplain now visible in various portions of the Front Range had been developed at an elevation not greatly above sea-level, and that no changes of level had occurred in the interim between the period of folding and the development of this peneplain, then the latter could be accepted with confidence as the datum-plane, and it would be proper to measure the height of the projected folds above the present height of the peneplain. This of course presupposes that the orogenic folding movements were accompanied by little epeirogenic uplift. If, however, there was general regional uplift along with the folding this can be treated as subsequently indicated. But there were, in all probability, some changes of level during this very considerable period of time between the folding and the peneplain. A rise of the sea consequent upon the transfer of sediment from the uplifted lands to the ocean floor might confidently be expected. But at most this would amount only to a few hundred feet.[1] Furthermore it is to be noted that such a rise of the sea-level is in the nature of a return to the late Cretaceous conditions of widely transgressive seas, and hence toward the conditions and level from which the Rockies arose.

Far more to be feared are possible uplifts due to vertical forces operating independently of folding movements. There are two possibilities: A general regional uplift might have affected the entire area more or less uniformly; or the change in level might have been confined to local upbowings, either within the granite areas of the main ranges where it would readily escape notice, or within the areas of folded sedimentaries, portions of which might have been raised without materially increasing the intensity of the folding. But on the other hand renewed horizontal thrusting which merely carried further the folding process would cause no harm provided the thickness of the folded shell were the same as in the previous episode of folding. If the thickness were different, however, such later deformation would add a complicating factor. The folded Eocene volcanics at Windy Gap on the Grand River show that the folding cannot all be assigned to a single period, and this later folding may have been fully as intense in the region in question as the earlier Laramide diastrophism.

---

[1] R. D. George has estimated that the cutting away of the present continents and the deposition of the material in the ocean basins, would raise the sea-level about 650 feet. Chamberlin and Salisbury, *Geology*, I, 545.

Although these are admittedly embarrassing factors which may have operated to some extent and which, if they did, lessen the accuracy of the final results, still it is believed that quantitatively they probably were not of sufficient magnitude to alter the general purport of the results. When it is noted that the average height of the folded tract throughout the entire section, according to measurements, is slightly over 13,000 feet above the datum-plane, it is apparent that a concealed, or unrecognized, uplift of 1,000 feet, or even 2,000 feet, will not change the order of magnitude or general significance of the results. The former would amount to but 7.7 per cent of the total; the latter to 15.4 per cent of the total. It is also frankly to be recognized that the method of projecting folds involves at best some error, and that when granite areas are included in the section the possible error becomes just so much greater. Such errors are inevitable owing to the limitations which the section imposes, and in the Colorado Rocky Mountain case they are considerable. Hence it is believed that refinements of method such as the introduction of corrective factors for the uplifting of the folded region during the interval between the folding and the peneplain stage, or for changes in the sea-level, or for the possible spreading and settling of the high standing mountainous masses, or for other changes, cease to be very vital in this case, though thoroughness in analysis requires their recognition. In any case they would be likely to offset one another more or less. The measure of inevitable error inherent in the section itself is so considerable that it is scarcely worth while to attempt to evaluate these subordinate factors.

Recognizing the limitations of the method, but believing that the probable errors from these complicating factors are not great enough quantitatively to affect seriously the general conclusions, and that in any case they are probably less than the errors which will always stand in the way of a dynamic study of these ranges, owing to scarcity of data upon the granite areas, this investigation will proceed on the hypothesis that the peneplain level today represents with fair approximation the original level from which the folds arose. A hypothetical picture of this situation might be as follows: The folding of the Rockies was accompanied in all probability by some general uplift of the continent as a whole. Suppose that this uplift brought the Great Plains belt adjoining the Rockies to an elevation of 2,000 feet above the sea. Let us assume that the base-leveling process in developing the peneplain caused a rise of the sea to the extent of 500 feet. Then the peneplain, in order to constitute the correct datum-plane, should have been formed at an elevation of 1,500 feet above sea-level. Whether this imperfectly reduced Colorado peneplain, featured by many large monadnocks and nearly a thousand miles by the existent drainage routes from either the Gulf of Mexico or the Pacific Ocean, may reasonably have developed at this elevation is left to the reader to judge.

The average height of the reconstructed folded surface above this natural datum-plane was found to be as follows:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	1.51
No. 2. St. Vrain sheet	3.13
No. 3. Allen's Park sheet	3.90
No. 4. Continental Divide sheet	4.03
No. 5. Granby sheet	2.18
No. 6. Sulphur Springs sheet	1.68
No. 7. Troublesome sheet	2.42
No. 8. Gore Range sheet	2.40
No. 9. State Bridge sheet	2.24
No. 10. Castle Peak Sheet	1.62
No. 11. Gypsum sheet	1.98
No. 12. Dotsero sheet	2.54
No. 13. Glenwood Springs sheet	2.83
No. 14. Grand Hogback sheet	0.43

These figures should therefore represent, subject to the abovementioned qualifications, the degree of uplifting which has resulted from the folding process.

It will be seen that in the matter of uplift the Grand Hogback sheet falls far short of all the others and appears to be in a class by itself. An inspection of the Grand Hogback section reveals the fact that, while the eastern half of the sheet shows moderate uplift, the western half, on the contrary, indicates subsidence, for the upper surface of the Cretaceous there dips more than 5,000 feet below the datum-plane. Only Tertiary rocks are exposed at the surface in the western portion, and in fact the geological map of Colorado shows that these Tertiary rocks continue to the southwest without interruption for fully 50 miles more—even to within 20 miles of Grand Junction. This area west of the Grand Hogback constitutes the southeast portion of the extensive Uinta Basin, which is a structural basin filled with thick Eocene deposits. Throughout this basin of heavy Eocene sedimentation the upper surface of the Cretaceous has been depressed below our datum-plane.

The Grand Hogback is a sharp ridge of upturned resistant strata, which marks the location of a sharp monoclinal flexure between the uplifted Rocky Mountain region on the east and the downwarped Uinta Basin to the west. A study of the Grand Hogback cross-section sheet raises the question whether subsidence of this basin of Eocene sedimentation may not have been as important in developing the Grand Hogback monoclinal flexure, as upwarping on the Rocky Mountain side. But whether subsidence or uplift has been the more effective in bending the strata, the earlier Eocene beds in any case exhibit essentially as much folding as the underlying Cretaceous, indicating that the flexing for the most part has come after the Laramide disturbance. Later studies may show whether or not this bending was synchronous with the episode of folding which affected the Middle Park beds near Windy Gap. Because the extent of the subsidence suffered by the Uinta basin interferes with any reliable determination of uplifting on its borders, the Grand Hogback sheet will not be included in the section used for estimating the thickness of the folded Rocky Mountain shell. The measured section will thus end with the western edge of the Glenwood Springs sheet, $1\frac{1}{4}$ miles southwest of Glenwood Springs.

Since the country was corrugated into the lofty folds portrayed by the reconstructed cross-section, the high-standing areas have been subject to some relaxational movement. Portions of the area have settled by the process of normal faulting. It is to be noted that all the faults shown in the cross-section are located on the limbs of anticlines or in the plateau-like region between State Bridge and Glenwood Springs. The faults appear to shun the synclinal troughs. This would imply a spreading of the anticlinal arches accompanied by downslipping on the sloping flanks. That more of these normal faults are located on the western limbs of anticlines than on the eastern may have been a chance matter of local conditions and so of little import, or may possibly point toward a westward creep in the relaxational process. There are several theoretical reasons why the latter might be looked for, but the evidence is so meager as to merely raise the query. Since the settling along these faults took place presumably after the folds had attained their growth, the foregoing estimates of the height of the folded tract have been made on the basis of the original folds.

THE THICKNESS OF THE FOLDED SHELL

Having estimated the crustal shortening and the vertical bulging which have arisen from the folding, the depth of the folded zone is to be calculated. According to our formula, the product of the present horizontal length of the folded section times the vertical uplift equals the product of the shortening times the depth of the folded shell (Fig. 12). This is true except in so far as there has been an actual change in volume due to the compacting of materials under the comprehensive stresses. As discussed in a previous paper,[1] the amount of shortening due to the mashing of the strata and the compacting of materials during folding is relatively small in comparison to that resulting from corrugation—in all probability not more than 5 per cent. Furthermore, the shortening due to the compacting of the rocks is more or less offset by subsequent elongation of the strata arising from jointing, from the opening of fissures, and the penetration of igneous intrusions.

[1] *Jour. Geol.*, XVIII (1910), 236–37.

But as any corrections for these qualifying factors on the basis of present information would be essentially arbitrary, they will be passed over for the present. Corrections to cover them can, however, be introduced at any subsequent time if the necessary information should become available, or if it should be felt that these factors are of sufficient quantitative importance to justify their further consideration.

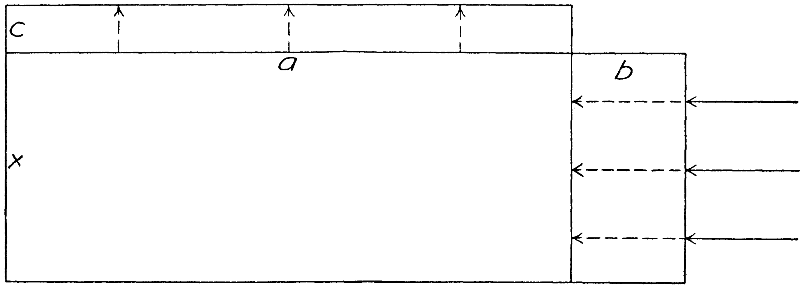

FIG. 12.—Diagram to illustrate the method of calculating the depth of a folded block.

a = the present horizontal length of the section
b = the shortening caused by the folding
c = the upbowing resulting from the folding
x = the depth of the deformed block
Then $(a+b)x=a(x+c)$

$$ax+bx=ax+ac$$

$$x=\frac{ac}{b}$$

Using the method above outlined, the thickness of folded shell was calculated separately for each ten-mile sheet of the Lyons–Grand River section. The results were as follows:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	13
No. 2. St. Vrain sheet	34
No. 3. Allen's Park sheet	48
No. 4. Continental Divide sheet	45
No. 5. Granby sheet	20
No. 6. Sulphur Springs sheet	26
No. 7. Troublesome sheet	54
No. 8. Gore Range sheet	87
No. 9. State Bridge sheet	35
No. 10. Castle Peak sheet	81
No. 11. Gypsum sheet	84
No. 12. Dotsero sheet	88
No. 13. Glenwood Springs sheet	107

The results are presented diagrammatically in Fig. 13, in which each section has been represented as though it were an isolated rectangular block, no attempt being made to accommodate these blocks to one another as was done undoubtedly in the real case.

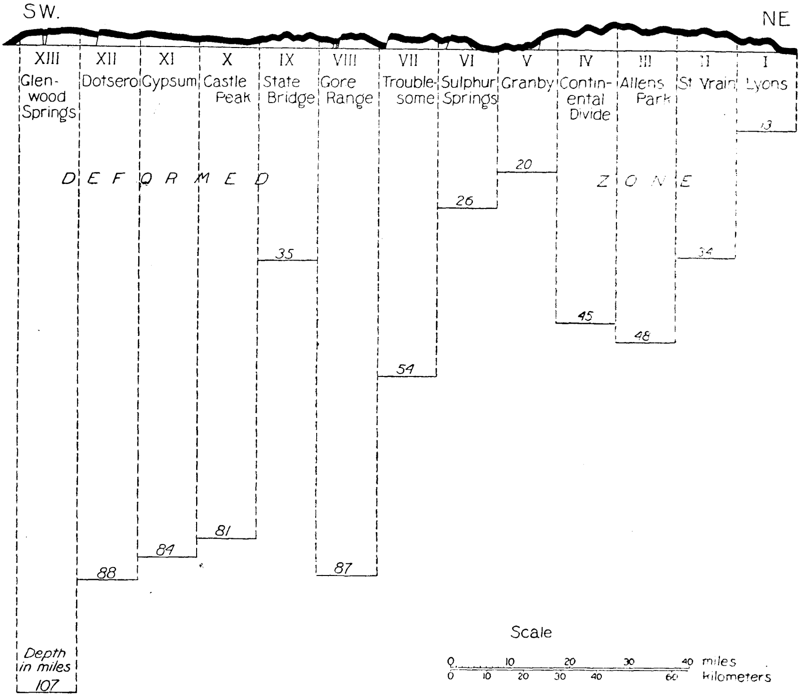

FIG. 13.—Diagrammatic cross-section of the deformed zone for this portion of the Colorado Rockies. The thirteen separate blocks are numbered in order from northeast to southwest. The heavy black line gives a restoration of the Laramie and Mesa Verde formations and thus represents the original folded surface. The depth in miles is given at the bottom of each block. No attempt is made to bound the deformed zone by a curved lower surface, as was presumably the actual case in the field.

Curved boundary lines would certainly conform more closely to nature, but nothing more than the strictly diagrammatic block-outline is ventured here.

Fig. 13 appears to show that beneath the two principal granite ranges, which today mark the lines of greatest upfolding, the disturbed zone reached deeper levels than on the immediate flanks of the upfolded belts. The granite mountain belts are more deeply rooted than the less uplifted strips adjacent. They constitute the true Rocky Mountains of this latitude.

According to the testimony of the Lyons sheet the folded shell of the Front Range thins rapidly as it approaches the Great Plains. This repeats in type, though less strikingly, the rise of the boundary shearing plane on the western border of the Appalachian Mountains near Tyrone, Pennsylvania.[1] Neither the Lyons section nor the Tyrone section developed an actual fracture, though they suggest an approach to it. But on the western border of the Appalachians farther south the boundary shearing plane has actually emerged from the depths as a strong thrust fault which separates the disturbed mountainous belt on the east from the region of horizontal strata on the west. This is especially conspicuous in Tennessee. In close analogy to this, in Montana and Alberta, the Rockies are separated from the Great Plains by an overthrust fault, or faults, of great displacement. These instances pointedly suggest the generalization that bordering thrust faults, particularly on the inland margin of a strongly deformed mountain belt away from the assumed active oceanic segment, are a common, and if so significant, phenomenon, especially as they accord with the theory of mechanics. With greater intensity of thrusting and the appropriate rock materials, the great upfold in the foothill belt of the Colorado Rockies would presumably have passed into a bordering thrust fault.[2] Such a bordering thrust fault appears to have developed on the east flank of the Wet Mountains, where that range continues the Rocky Front *en échelon*, south of the Arkansas River.[3] The pre-Cambrian granite has been thrust eastward over the Cretaceous strata of the plains and lower foothills, and also in one place over a conglomerate which has been classed tentatively as Arapahoe.

The westernmost four divisions of the plotted section, representing the region of but slightly disturbed strata between State

---

[1] *Jour. Geol.*, XVIII (1910), 245, Fig. 6.

[2] Some local fracturing did develop at Boulder and at Golden. See Ziegler, *Jour. Geol.*, XXV (1917), 728–40.

[3] C. W. Washburne, "The Canon City Coal Field, Colorado," *U.S. Geol. Surv., Bull. 381* (1910), p. 342 and Pl. XVIII.

Bridge and the Grand Hogback, constitute in reality a plateau region rather than a folded mountain area. This strip is to be considered the southeastern extension of what has been called the White River plateau. In fact the deformation in the westernmost forty miles of the chosen section was so slight that this strip was not originally included in the folded mountain section measured in 1915. It was added in 1916. Fig. 13 indicates that beneath this region of plateau-like uplift the lateral thrusting movement has been distributed through a thick zone which has been deformed only slightly.

To interpret Fig. 13 the deforming movement pictured as the result of thrusting from the west was distributed at first through a thick shell in the plateau region, but in this thick zone it reached only a low degree of intensity. The region was in consequence but feebly wrinkled. But in the region next east, where the Grand River today turns abruptly northwestward near State Bridge, the activity was concentrated in a thinner movable zone which was far more sharply folded. This marks the western flank of the folded belt which culminated in the Gore or Park Range. Next east of this, less folding in the middle of the Gore Range indicates greater depth of shell there, followed by thinning again on the eastern flank of the Gore Range. The disturbed mass became thinner again in the Middle Park region, where the uplifting was relatively less, and then it deepened rapidly beneath the Front Range, where the uplift was greater, again thinning out rapidly to the edge of the Great Plains, which border the folded belt on the east. In this way the Front Range repeated the wedge-shaped block of the Park Range.

These results are based on the assumption that the shortening has remained the same throughout the full depth of each deformed block. If the shortening, in reality, increases with depth these figures are overestimates of the thickness of the folded shell. But on the other hand, if it be true that there was less folding and less shortening in the deeper portions of these blocks, these figures are underestimates of the depths to which the folding extended. Of the two alternatives the latter seems the more probable. With increasing depth below the surface, the resistance of the rocks to deformation steadily increases, thus necessitating greater and greater stress differences in order to cause folding. Unless the stress differences increase as rapidly as does the resistance with increasing depth below the surface, folding, instead of becoming easier in the deeper levels as the time-honored doctrines have taught, becomes more and more difficult and hence less effective.[1] Daly has called attention to the fact that in the Selkirk Range of British Columbia the Shuswap terrane of presumable Archean age has escaped much of the folding which so powerfully affected the younger rock systems. The basement rocks show comparatively slight deformation, from which Daly concluded that "the earth shell engaged in the post-Shuswap orogeny was only a few miles, perhaps 6 or 8 miles, in depth. Over the Shuswap terrane this shell was thrust and crumpled."[2]

Beneath the surface the sharpness of folding probably at first increases down to a level of greatest folding, below which it again diminishes. With increasing depth below the level of sharpest folding, the folds of the wrinkled shell may either die out gradually or the adjustment may be accomplished by shearing between the upper, more movable portion and the lower, less movable portion. Fig. 13 is based on the assumption of undiminished intensity of folding throughout the full depth of each deformed block, and hence calls for adjustment by shearing below. In the actual case the adjustment was probably accomplished, not by shearing alone, but by some combination of the two processes. But at present the relative importance of the two cannot be decided, except upon arbitrary assumptions. Too much weight must, therefore, not be given to the precise figures for the depth of the various blocks.

Estimates of the depth of deformed shell by this method are subject to modification for such uplifts as were not occasioned by the horizontal compression. In this section of the Colorado Rockies it is quite possible that upbowing has recurred along the old lines of yielding during the critical interval between the folding of the mountains and the establishment of the peneplain, and any such vertical movement whose occurrence and extent have not been detected and duly covered by a correction, would reduce the accuracy of the calculated results. But on the other hand, any uplifts subsequent to the development of the peneplain do not in any way enter into the problem, for the adopted method of treatment eliminates their influence. The testimony of folded mountain ranges in general is to the effect that later episodes of yielding commonly follow along the lines of earlier folding, doubtless because they have become the lines of least resistance. These later episodes of diastrophism may obviously be either further folding under compressive stress or uplifts with but little folding. The effect of the latter possibility in the case under discussion would be to increase the height of the folded section, without correspondingly adding to the measured shortening, and thus make the calculated depths of the Gore Range block and Front Range block too great. The other alternative of further folding along the old lines is less serious, for, as has been stated before, the outcome of the computations will be the same whether the folding all took place at one time or at different times, provided the same thickness of shell was affected each time. If two or more episodes of folding deformed different thicknesses of shell, the computed depth resulting from the adopted method of treatment would be in the nature of an average. In this connection it is of significance to note the statement of Hills that the post-Bridger folding was essentially a continuation of the post-Laramie folding, for the second movement began where the first terminated, and if the post-Laramie movement had been further continued the resulting structure might ultimately have been the same.[1]

---

[1] F. D. Adams and J. A. Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV (1917), 597–637.

[2] Reginald A. Daly, "A Geological Reconnaissance between Golden and Kamloops, B.C., along the Canadian Pacific Railway," *Geol. Survey of Canada, Mem. 68* (1915), pp. 53–55.

In contrast to uplifting, any subsidence of intermontane basins of deposition, or local downwarping, during the critical interval between the mountain folding and the development of the peneplain would tend to offset the bulging effect of the folding process, and thus lead to a too low estimate of the height of the folded tract. This in turn would result in giving an underestimate of the depth of the folded block. In certain portions of the Granby, Sulphur Springs, and Troublesome areas, beds of Uinta age occupy several basins below the peneplain level. The position of these beds strongly suggests a sinking of these basins under the accumulation of early Tertiary times. Though the extent of the settling probably was not great, still it may have been sufficient to cause the calculations to assign a somewhat too meager depth to the rather shallow Granby and Sulphur Springs blocks.

---

[1] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), 419.

In the foregoing computations only the crustal shortening at right angles to the trend of the ranges has been considered. But folds are properly considered in three dimensions, and some longitudinal warping and pitching of the folds is to be expected. Longitudinal warping would involve crustal shortening in a direction parallel to the trend of the range and at right angles to the shortening above considered. The folds measured in the Lyons–Grand River section exhibit pitching in some places, but this did not appear sufficiently pronounced to justify the extra field work necessary to measure the northwest-southeast warping for the different sections. The warping at right angles to the main folding was most apparent in the State Bridge and Glenwood Springs sheets. This minor warping, like the major folding, causes upswelling of the folded tract. Hence in practice the effect of ignoring the minor warping in the direction of the ranges is to assign all the observed upswelling to the work of the major folding and thus obtain an overestimate of the depth of the folded zone.

There are therefore certain subsidiary considerations, such as uncorrected uplifts subsequent to the folding, and the neglect of upswelling from longitudinal warping whose influence is to cause overestimates of the depth of folded shell. But over against these is the uncorrected sinking of certain areas of Eocene sedimentation, and the assumption of uniform shortening throughout the full thickness of each deformed block, whose probable influence is to cause underestimates of the depth. In all probability each of these is the source of some error. How nearly they offset each other and so cancel out of the equation cannot be told at present. But they probably do not greatly modify the general order of magnitude of the calculated results.

GENERAL DISCUSSION AND CONCLUSIONS

These studies would seem to show that the Colorado Rockies differ in several notable respects from the folded Appalachians of Pennsylvania.

1. They have suffered, in the first place, much less horizontal compression. From the Great Plains to the Uinta Basin, 140 miles of country were compressed into 132 miles, thus involving a shortening of only 8 miles, while west of Harrisburg alone 81 miles of strata were squeezed into 66 miles of present Appalachians, which means a shortening of 15 miles in this much narrower belt. This does not include the folding in the metamorphic belt east of Harrisburg.

2. A much thicker shell seems to have been involved in the Rocky Mountain diastrophism than was actively deformed in the Appalachian folding. The apex of the Pennsylvania Appalachian wedge was but 32 miles below the surface, while the roots of the Gore Range reached a depth of 87 miles and the plateau tract near Glenwood Springs had a depth of 107 miles.

3. Vertical lifting and plateau-forming movements have been more pronounced in the Rockies than in the Appalachians. This is indicated both by the outcome of this analysis, and also by the present high altitude of the Colorado Front Range peneplain, though the elevation of the latter, to be sure, came long after the principal folding, which is the basis of this investigation.

4. The formation of the Colorado Rockies was accompanied by much more vulcanism than the formation of the Appalachians.

These conclusions lead naturally onward to certain additional deductions and further applications. These specific results confirm the principle that there is an inherent relation between thickness of shell actively involved and intensity of deformation. This justifies the conclusion that mountain ranges displaying intense folding, thrust faulting, and dynamic metamorphism resulting from extreme horizontal compression are associated with a thin, shallow shell. This thin, movable shell, which has been greatly folded and faulted, shears upon the less yielding base beneath it. Ranges of this sort are the Appalachians and presumably the Jura, Alps, Scottish Highlands, Scandinavian chain, and others of great shortening and intense horizontal thrusting. If the active crumpling in a range like the Alps were not confined to a very thin shell the resulting vertical bulge would be stupendous.

Those ranges in which a much thicker shell has yielded to the stresses are characterized by open, gentle folding, only moderate shortening, but more pronounced vertical lifting. The Colorado Rockies belong to this group. Moderate folding distributed through the thicker zone accomplishes the same amount of vertical bulging as greater shortening of a thinner zone. Shearing along a few well-defined planes may well be a less important means of adjustment beneath the thicker deformed zone than beneath the thinner one. Adjustment in the thicker zone is probably due to gradual accommodation by the slow dying out of folds below, with perhaps more or less local, distributive shearing. Upward yielding in the direction of least resistance being relatively more conspicuous than horizontal movement when a thick shell is deformed, this type of mountain building crowds closely on the borders of the plateau-forming type of diastrophism. The western portion of the Lyons–Grand River section, from State Bridge to the Grand Hogback, where the disturbed zone had a thickness rising from 81 to 107 miles, portrays what was essentially a plateau uplift, and suggests the actual merging of this mountain type into the plateau type.

An incidental feature of some significance is the bordering thrust fault observed in several instances on the inland margin of a strongly deformed mountain belt farthest removed from the oceanic segment from which the thrusting presumably has come.

Since the Laramide disturbance the Colorado Rocky Mountain region has been the scene of much vulcanism. The products of this, in places, have obscured the folded strata beneath, and thus have added materially to the difficulty of making an accurate cross-section of the mountainous belt. In general, Tertiary vulcanism has been a prevailing phenomenon throughout the Rockies from Montana to New Mexico. In the region of the present Appalachian Mountains, on the other hand, there has been very little vulcanism. There were the Upper Triassic lavas of the Newark series, to be sure, but they were east of the present mountains and, breaking out long after the Appalachian folding, they appear to be genetically related to faulting nearer the coast in a diastrophic movement which occurred toward the close of the Triassic. Lavas and tuffs caused no trouble in measuring the Pennsylvania mountainous section.

In view of the fact that the Pennsylvania Appalachians, which show less volcanic activity, have resulted from the crumpling of a comparatively thin surface shell, while the Colorado Rockies, with more extensive vulcanism, involved a thicker shell, it is suggested that there probably is a genetic relation between the depth to which the roots of a mountain range extend and the amount of vulcanism associated with it. It seems very rational a priori that if the zone disturbed in the formation of a folded range does not extend far below the surface, it would not be likely to lead to the generation of magmas nor greatly facilitate their escape if already present in the undisturbed depths below, even though the folded zone itself may be intensely deformed and shear strongly over the underlying base. But if, on the other hand, the disturbed zone reaches down to considerably greater depths, even though the deformation itself be not so intense, it may readily afford better opportunities for the generation or the rise of magma to the surface. At many points the difference in depth of disturbance may be sufficient to decide between a rise of magma and no upward movement of the magma, or by operating through relief of pressure, perhaps decide between potential magma and actual magma.

On theoretical grounds the thin-shell mountains should be accompanied in their growth by relatively little vulcanism, while the growth of thick-shell mountains should be attended by relatively greater outpourings of lava. Looking over the mountain systems of the globe one might select, as some of the conspicuous illustrations of sharp folding, great thrust faulting, and much crustal shortening, the Alps, the Scandinavian chain, the Scottish Highlands, the Backbone Range of Brazil, and perhaps the Rocky Mountains of Alberta. These would seem to be mountains of the thin-shell type as nearly as can be judged without actual measurements upon them. In each of these cases it will be observed that only moderate igneous activity was associated with the mountain building. This seems perhaps the more remarkable when it is considered that any great disturbance of the outer portion of the earth is likely to stimulate outward movements of liquid magmas, and in some cases through relief of pressure actually to cause liquefaction and the development of magmas.

As representatives of the thicker-shell type of mountains in which vertical movements are more pronounced, and horizontal thrusting and shortening less conspicuous, one might select in addition to the Colorado Rockies, the Cascades on the Pacific Coast,[1] the great chains of Andes, particularly the Western Andes, and the Abyssinian Mountains. The extravasation of vast floods of lava marked the growth of these ranges. In the light of this inquiry, it may be inferred that these mountains had deeper roots than the more sharply folded ranges, and that this greater depth of disturbance was an important factor in causing the greater igneous outbursts.

In final summation it may be remarked that within Colorado the Rocky Mountain system is characterized by open, gentle folding, moderate crustal shortening affecting a zone several scores of miles in depth in its deeper portions, by strong uplifting, and by the extrusion of much lava. Extending the range of view, it is to be noted that this dominantly vertical diastrophism with its ample outpourings of lava is typical of much of the western United States. On the other hand, in northwesternmost Montana and throughout Alberta, the ranges of the Rocky Mountain system exhibit low angle thrust faulting on a grand scale, greater crustal shortening which presumably has affected a thinner surface shell, and has been accompanied by less volcanic activity. It thus appears that a single mountain system of great length may develop both types of deformation in different portions of its extent.

---

[1] See Bailey Willis, "Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range," *U. S. Geol. Surv., Prof. Paper 19* (1903), pp. 95–97.